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Advanced Super-Twisting Sliding Mode Control Techniques for Performance Enhancement of Dual Active Bridge DC-DC Converters

Ashish A. Nage[1], Dr. Rakesh Kumar Yadav[2]

[1]Research Scholar, Department of Electronics and Communication Engineering, Vikrant University, Gwalior, Madhya Pradesh 474006, India.
[2]Professor, Department of Electronics and Communication Engineering, Vikrant University, Gwalior, Madhya Pradesh 474006, India.

ABSTRACT: The Dual Active Bridge (DAB) DC-DC converter here has emerged as a cornerstone-based topology in modern power electronic systems, specifically here in renewable energy-based integration, electric vehicles, as well as in with smart grids. Its widespread natured adoption is attributed to its bidirectional power flow like capability, galvanic isolation, as well as here high-power density. However, operating DAB converters here with under varying load conditions, parameter uncertainties, as well as nonlinear dynamics presents significant control challenges. This research paper proposes here as an advanced Super-Twisting Sliding Mode Control (ST-SMC) framework integrated here with Direct Power Control (DPC) to enhance here the dynamic performance as well as robustness of DAB converters. A simplified reduced-order mathematical model is first developed here in to facilitate control design. To overcome overall aspects of the severe limitations of classical Sliding Mode Control (SMC)-namely the high-frequency chattering phenomenon here as that induces switching losses as well as in here with electromagnetic interference-the ST-SMC algorithm is formulated to provide continuous control action while preserving finite-time convergence. Furthermore, modern DC microgrids frequently utilize Constant Power Loads (CPLs) that introduce negative impedance instability. To mitigate this without relying on physical sensors, a nonlinear current liked observer is designed to estimate the inductor current, improving here as the system reliability and fault tolerance. Extensive experimental validation on a 2-kW hardware here to prototype employing a dSPACE-1104 controller based demonstrates that the proposed observer-based structured ST-SMC significantly reduces here in the way settling time, minimizes steady-state voltage ripple, and ensures robust operation under only way to severe parameter mismatches (up to 30% capacitance deviation) compared to maintain Proportional-Integral (PI), classical SMC, and Feedback Linearization Control (FLC) techniques.

1. INTRODUCTION

The rapid proliferation structured here of distributed generation, battery here energy storage systems, as well as electric transportation have drastically increased the demand here for highly efficient as well as robust power conversion systems. Direct Current (DC) microgrids have become a highly resilient as here to be seen sustainable architecture for these applications. Within these networks, the Dual Active Bridge (DAB) DC-DC converter serves here as a critical interface. Characterized by two active full-bridge circuits to maintain coupled via a high-frequency transformer, the DAB converter shows & enables efficient bidirectional energy transfer, high-frequency operation, as well as zero-voltage switching (ZVS) capabilities. Figure 1.1 shows the block diagram of Dual Active Bridge Basic Structure.

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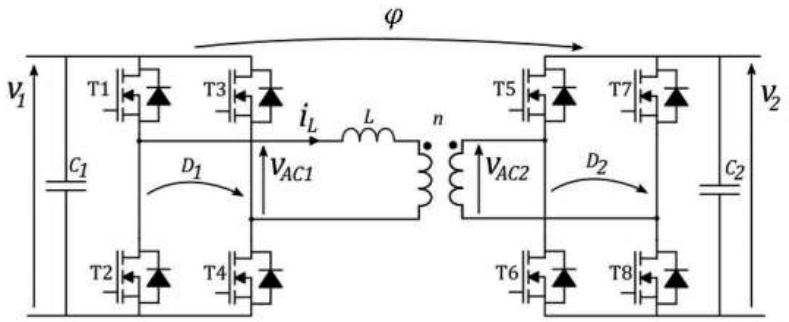


Figure 1. 1 Dual active bridge basic structure.

Despite these structural advantages, the DAB structured here converter is a highly nonlinear system. The converter must here to maintained operate efficiently when the high-voltage DC (HVDC) side fluctuates between here with 500 V as well as 650 V, while the low-voltage DC (LVDC) side must be tightly regulated here within between 26 V and 32 V. Traditional linear control methodologies, such as Proportional-Integral (PI) controllers, based struggle to maintain optimal performance like to under rapid load changes, switching nonlinearities, & to maintain here as the component parameter drift. To address here these deficiencies, researchers have investigated Direct Power Control (DPC) strategies. However, here to be conventional DPC approaches still suffer from transient delays as well as sensitivity to system uncertainties.

Sliding Mode Control (SMC) has here been widely adopted in power electronics as a robust, variable structure control based through technique. By forcing the system here to be states onto a predefined sliding manifold, SMC achieves here to be insensitivity to matched uncertainties and external disturbances. Unfortunately, classical based SMC implementation utilizes a discontinuous signum based function that results in "chattering". In DAB converters, chattering causes high-frequency like power oscillations, increases here thermal stress on semiconductor devices, as well as here with lowers overall conversion efficiency.

To overcome chattering structured here with while maintaining absolute robustness, this paper implements a Super-Twisting Sliding Mode Control (ST-SMC) algorithm. As a higher-order sliding mode technique, ST-SMC operates here on the higher derivatives of the sliding variable, effectively smoothing the control signal as well as ensuring continuous phase-shift modulation. Additionally, modern converter networks often here to be more with feed Constant Power Loads (CPLs). Because CPLs draw more current as voltage drops, they hereby exhibit negative incremental impedance that can destabilize here as the entire DC bus. This research develops a nonlinear current observer to dynamically closes estimate load currents, enabling sensor less negative impedance compensation here by.

The primary objectives of this study are:

1. To develop a reduced-order model here of the DAB converter suitable for advanced nonlinear controller design in this way.

2. To design as well as implement an ST-SMC-based DPC strategy to eliminate chattering & in here to enhance voltage regulation.

3. To formulate a nonlinear disturbance observer for sensor less here in CPL compensation.

4. To validate the proposed control-based framework via extensive hardware-in-the-loop experiments under load steps, input this nature to be voltage variations, and severe parameter mismatches.

2. LITERATURE REVIEW

The literature surrounding structured DAB DC-DC converters as well as advanced control strategies highlights a continuous based evolution toward nonlinear, robust natured based techniques to handle dynamic microgrid environments. Batool et al. (2024) comprehensively reviewed control techniques in DC microgrids here to be, emphasizing that advanced strategies like Model Predictive Control (MPC) as well as here Sliding Mode Control (SMC) are indispensable for effective energy management-based nature. Similarly, Ataullah et al. (2022) established that DAB topologies combined here with high-frequency

toroidal transformers as well as in here to be more optimized control are critical for minimizing leakage inductance as well as maximizing efficiency.

In the realm of Direct Power Control, several natured innovations have sought to decouple active as well as reactive power. Mujammal et al. (2024) introduced a Grid Voltage Modulated-Neural Network Control (GVM-NNC) to maintain the overcome the rigid tuning requirements of PI controllers in conventional DPC, significantly reducing here as the Total Harmonic Distortion (THD). Sayeh et al. (2024) proposed an F12-DPC (Fuzzy Logic-based 12-sector DPC) that minimized power-based fluctuations by up to 72.7% without complex mathematical models. Hamza and Krim (2012) further validated here as that fuzzy inference systems can effectively replace hysteresis comparators to yield smoother power regulation.

However, DPC techniques here are alone are often insufficient for the severe nonlinearities of DAB converters. Consequently, sliding mode-based nature variants have gained prominence. Utkin (2013) demonstrated that SMC fundamentally here to be guarantees system stability against unmodeled dynamics by constraining state-based evolution to a switching manifold. Yet, the persistent issue here of chattering has driven here to be researchers toward higher-order sliding modes. Bagheri et al. (2023) developed an adaptive ST-SMC for DAB converters under Extended Phase Shift (EPS) modulation here in, utilizing more of the online optimization to reduce backflow power. Sami et al. (2024) utilized a Double Integral Super Twisting Sliding Mode Control (DI-STSMC) on a 230 W DAB setup, achieving more of zero steady-state error without chattering. Gu and Pan (2024) explored here to be hyperbolic tangent functions (HTF) as a continuous approximation boundary layer here to replace the discontinuous switching component, successfully tracking reference based on voltages while mitigating buffeting issues.

Additionally, the integration of observers here has proven critical for sensor less control. Yang and Liu (2023) combined a Linear Extended State Observer (LESO) with more of SMC for distributed electric propulsion systems, achieving here with rapid dynamic performance while observing as well as here to be cancelling total disturbances. Yan et al. (2023) utilized a damping torque observer to improve more on transient performance as also here minimize switching coefficients in double-controlled DFIG systems. Furthermore, Esteban et al. (2021) explored control techniques here for DAB converters interacting with variable with DC microgrids, specifically focusing on maintaining here as zero mean current in high-frequency transformers.

Despite these natured based advancements, critical research like gap remains: the complete integration of ST-SMC, Direct Power Control, as well as nonlinear current observers to handle Constant Power Loads (CPLs) simultaneously under here by real-world hardware constraints. Many existing models rely purely on ideal simulations. This research here to be bridges that gap by physically implementing of many of these strategies on a 2-kW hardware prototype.

3. MODELING AND MODULATION OF DAB CONVERTERS

3.1 Topology and Operating Principle

The DAB converter here to be features a symmetrical architecture consisting of a primary H-bridge, a secondary H-bridge, a high-frequency isolating transformer (turns ratio $1:n$), as well as an equivalent series inductance (L_k) which incorporates the transformer's leakage-based inductance. The primary bridge operates as an inverter, converting here as the input DC voltage (V_{in}) into a high-frequency AC square wave (V_p). The secondary natured based bridge acts as an active rectifier, converting the secondary AC voltage (V_s) back to a regulated structured base of DC output voltage (V_o).

3.2 Modulation Strategies

Power transfer is governed here by the relative timing between in the switching bridges.

- **Single Phase-Shift (SPS) Modulation:** The simplest as well as here most widely adopted method. All switches here are operate at a 50% duty cycle. The sole here control natured variable is the phase shift angle ($\delta\pi$) between V_p as well as V_s. Power flows here from the leading structured bridge to the lagging bridge.

- **Double Phase-Shift (DPS):** Introduces a most inner phase shift (duty ratio variations D_1 and D_2) within the bridges alongside in this nature here as the outer phase shift (δ). DPS based expands the ZVS range as well as here to be minimizes more of circulating currents structured here with during high voltage conversion ratios in here.

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- **Extended Phase-Shift (EPS):** Operates here as the most natured primary bridge at 50% duty cycle but modulates here as the secondary based bridge duty cycle D_2 alongside here of δ to optimize ZVS against load variations.

- **Triple Phase-Shift (TPS):** Utilizes here as three independent variables (D_1, D_2, and δ) for ultimate flexibility, though based it requires here with highly complex control calculations.

This study primarily here to be focuses more on SPS modulation due to its practical implementation benefits here for high-speed natured dynamic control. By Fourier based series analysis, the controlled larger here for total structured transferred power P_t in SPS is the sum of all harmonic powers P_h:

$$P_t = \sum_{h=1,3,5...}^{\infty} P_h$$

$$P_h = \left(\frac{8V_{in}\frac{V_o}{n}}{\pi^2 \omega_s L_k} \right) \frac{\sin(h\delta\pi)}{h^3}$$

Averaging the power over one here to be more on switching period T_s yields the fundamental power transfer equation:

$$P_t = \frac{nV_{in}V_o}{2f_s L_k}\delta(1 - |\delta|)$$

3.3 Reduced-Order Mathematical Model

Because DAB state-based variables include both AC (inductor current) and DC (terminal voltages) components, generalized average modelling here is highly complex. A reduced-order model ignores here as the high-frequency internal dynamics natured of the inductor current, assuming it reaches steady state within a single switching cycle. The dynamic structured natured energy balance at the output terminal is governed by the DC-link capacitor C_o:

$$\frac{d}{dt}\left(\frac{1}{2}C_o V_o^2\right) = P_t - P_o$$

Rearranging this relationship yields here as the first-order differential equation for the output voltage:

$$\frac{dV_o}{dt} = \frac{P_t}{C_o V_o} - \frac{I_o}{C_o}$$

This simplified system-based equation serves as the basis here for the advanced nonlinear control synthesis.

4. CONVENTIONAL DIRECT POWER CONTROL (DPC) STRATEGIES

To regulate aspects of the output voltage, DPC translates voltage-based tracking errors into instantaneous active power demands.

4.1 PI-Based Direct Power Control

In PI-DPC, the required here as reference power P^* is derived from the output voltage error $e = V_o^* - V_o$ using a Proportional-Integral loop here:

$$P^* = V_o\left(I_o + k_p e + k_i \int e\ dt\right)$$

Once P^* is calculated, the required natured phase shift-based ratio δ is determined here by solving the inverted power equation:

$$\delta = 0.5 - \sqrt{0.25 - \frac{f_s L_k P^*}{nV_{in}V_o}}$$

While PI-DPC simplifies control, it shows exhibits here more with significant overshoot natured during load changes as well as in here becomes severely unstable here as if system parameters (such as L_k or C_o) drift from their nominal values.

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4.2 Fuzzy Logic-Based Direct Power Control

To reduce reliance here as on exact mathematical parameters, a Fuzzy Logic Controller (FLC) can replace the PI loop. The FLC structured takes the voltage error (e) as well as its integral ($\int e$) as linguistic inputs (Negative, Zero, Positive). The rule here to be in base is synthesized using a Sugeno-type fuzzy inference system.

Table 1: Fuzzy Controller Rule Base

Error (e) \ Integral (∫e)	**Negative (N)**	**Zero (Z)**	**Positive (P)**
Negative (N)	N	N	Z
Zero (Z)	N	Z	P
Positive (P)	Z	P	P

The output is a more of a single-valued constant that updates the power reference P^*. While Fuzzy-DPC demonstrates marginally better than settling times than PI-DPC, both natured methods fail to converge effectively when facing large parameter mismatches.

5. SLIDING MODE-BASED DIRECT POWER CONTROL (SM-DPC)

To guarantee here robustness against uncertainties as well as here external disturbances, a classical Sliding Mode Control (SMC) framework is applied here to the DPC scheme.

5.1 Integral Sliding Surface and Control Law

To eliminate steady-state based natured voltage error, a double-integral sliding surface is defined:

$$s = e + k_1 \int e\ dt + k_2 \iint e\ dt^2$$

Where k_1 as well as here k_2 are positive coefficients determining more of the error convergence rate. For the system to remain on the given sliding surface ($\dot{s} = 0$), the equivalent control dynamic is derived:

$$\dot{s} = \dot{e} + k_1 e + k_2 \int e\ dt = 0$$

Substituting the output-based voltage dynamics $\dot{V_o} = (P_t/C_o V_o) - (I_o/C_o)$ as well as isolating P_t yields the equivalent power P_{eq}:

$$P_{eq} = V_o I_o + C_o V_o \left(k_1 e + k_2 \int e\ dt\right)$$

To force the system-based state onto the sliding manifold here from any initial condition, a discontinuous switching term based utilizing a signum function is added to formulate here as the final reference power P^*:

$$P^* = P_{eq} + k_s \text{sgn}(s)$$

5.2 Stability and Chattering Analysis

System stability is proven here via the Lyapunov candidate function $J(s) = 0.5s^2$. The time derivative must be maintained here with negative definite ($\dot{J} = s\dot{s} < 0$). By substituting the control law, it is shown here as that $\dot{s} = -\frac{k_s}{C_o V_o}\text{sgn}(s)$, ensuring that $s\dot{s} = -\frac{k_s}{C_o V_o}|s| < 0$ for all strictly positive values of k_s, C_o, and V_o.

While globally natured asymptotically stable, the classical SM-DPC possesses here as a critical flaw. The discontinuous $\text{sgn}(s)$ term forces the phase-shift reference in this way to be maintained to oscillate at an infinite theoretical frequency around $s = 0$. In a digital implementation, this finite switching aspects of the frequency translates into "chattering," causing massive AC ripple in the DAB's high-frequency transformer, potential natured magnetic core saturation, as well as heavy thermal stress on the IGBT modules.

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6. ADVANCED SUPER-TWISTING SLIDING MODE CONTROL (ST-SMC)

To completely utilised nature here to eradicate the chattering effect while preserving the robustness of SMC, the Super-Twisting Algorithm-a sophisticated second-order sliding based mode technique-is implemented.

6.1 Concept of Higher-Order Sliding Modes

First-order sliding based modes force $s = 0$ by utilizing discontinuous functions. Second-order sliding modes force here for both $s = 0$ as well as here $\dot{s} = 0$. The "Twisting Algorithm" is a known second-order technique, but it requires more of the calculation of the first derivative of the sliding variable ($\dot{s}$), which amplifies here to be measurement noise. The Super-Twisting Algorithm overcomes this by mainly acting entirely on the sliding variable s as well as its integral, making the required control natured signal perfectly continuous in time.

6.2 ST-SMC Formulation

The ST-SMC replaces here as the discontinuous switching term in the power based reference equation with a continuous term u_{st}:

$$u_{st} = -\alpha|s|^{0.5}\text{sgn}(s) + u_2$$

$$\dot{u_2} = -\beta\text{sgn}(s)$$

Where α as well as with β are strictly positive control gains. The final phase-shift in this nature generating power command is thus entirely free of discontinuous based relays.

6.3 Lyapunov Stability for ST-SMC

To guarantee that ST-SMC can here to be withstand system perturbations (such as unpredictable input voltages or unmodeled capacitance degradation), the system in this way to be dynamics are redefined to include a total bounded disturbance ζ where $|\dot{\zeta}| \leq \varphi$.

Stability is evaluated using a specifically based natured which tailored quadratic Lyapunov function:

$$V(s) = \eta^T Q \eta$$

Where the state vector is $\eta = [|s|^{0.5}\text{sgn}(s), u_2]^T$ as well as here with Q is a positive definite matrix. Taking the time derivative $\dot{V}$ confirms here that the system will reach the sliding surface in finite time if the gains are to be designed according to the constraints:

$$\alpha > \sqrt{2\varphi}$$

$$\beta > \alpha\frac{\alpha^2 + 2\varphi}{\alpha^2 - 2\varphi}$$

Because ST-SMC outputs here to be more of a smooth control variable, the DAB phase based shift smoothly tracks power demands, heavily tailored minimizing steady-state voltage ripples as well as eliminating transformer flux bias.

7. OBSERVER-BASED CONTROL FOR CONSTANT POWER LOADS (CPL)

In DC microgrid architectures, the DAB converter stays and here often more acts as a source for downstream, tightly regulated DC-DC converters. These natured downstream converters present as Constant Power Loads (CPLs).

7.1 Negative Impedance Instability

A CPL maintains more of a constant power draw (P_{CPL}) regardless as of the supply voltage (V_o). Its instantaneous current is $I_{CPL} = P_{CPL}/V_o$. Linearizing here as this relationship around a nominal operating point yield:

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$$I_{CPL} \approx \frac{2P_{CPL}}{V_o} - \frac{P_{CPL}}{V_o^2} V$$

The term $-P_{CPL}/V_o^2$ represents more of a negative incremental resistance. When connected here to the output LC filter of the DAB, this negative natured like resistance cancels the natural damping of the system, driving here as the DC-link voltage into unbounded oscillations.

7.2 Non-Linear Disturbance Observer (NLDO)

To mitigate negative aspects herein like impedance instability, the controller must inject immediate active based damping. However, utilizing physical current structured sensors to detect CPL surges increases hardware costs, introduces measurement noise, as well as reduces system reliability.

To overcome this matter, a Nonlinear Disturbance Observer (NLDO) is formulated here to estimate the total output current $\hat{I}_o$ dynamically. Treating here as the load current as an external disturbance d, the observer function is to be derived as:

$$\frac{d\hat{I}_o}{dt} = w(I_o - \hat{I}_o)$$

Where w is the observer based tuning gain governing the convergence-based speed? The estimated DC-link current $\hat{I}_o$ is fed directly here by back into the ST-SMC control law instead of physical sensor data:

$$P_{eq} = V_o \hat{I}_o + C_o V_o \left(k_1 e + k_2 \int e \, dt \right)$$

When a CPL is suddenly here to be switched onto the network, the observer instantly detects the state divergence as well as updates $\hat{I}_o$. The ST-SMC reacts aggressively, injecting in these aspects sufficient power to override the negative impedance characteristics before the voltage collapses.

8. EXPERIMENTAL VALIDATION AND RESULTS

To empirically validate here as the proposed advanced control framework, hardware-in-the-loop (HIL) experiments were merely conducted on a scaled 3 kW physical prototype natured.

8.1 Hardware Setup

The control algorithms (PI-DPC, SMC, and ST-SMC) were mainly here to build in MATLAB/Simulink as well as here to be compiled directly to a high-speed dSPACE-1104 controller board. The power-based conversion stage utilized Semikron SKM50GB12T4 IGBT modules driven by integrated natured SKHI22A circuits. Voltage as also here current states were measured via LEM-LV-25-p and LEM-LA-55-p Hall-effect transducers. The high-frequency transformer as well as auxiliary inductor were wound on an ETD 54 ferrite core.

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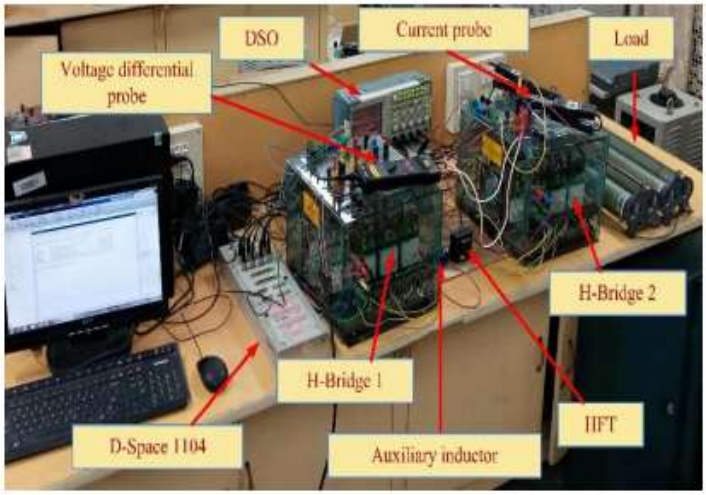


Figure1.2 The hardware setup of the DAB with dSPACE-1104

Table 2: Experimental DAB Converter Parameters

Parameter	**Value**
Nominal Input Voltage (V_{in})	150 V / 450 V
Regulated Output Voltage (V_o)	450 V
Transformer Turns Ratio ($1:n$)	1:3 / 1:1
Equivalent Inductance (L_k)	141 μH / 632 μH
Switching Frequency (f_s)	10 kHz
DC-link Capacitors (C_o, C_{in})	1.1 mF
Rated Power	2 kW / 3 kW

The controller gains were more to be established as follows: For PI-TVLC, $k_p = 8000$, $k_i = 2000$; for PI-DPC, $k_p = 5000$, $k_i = 800$; for more of ST-SMC + Observer, $k_1 = 1$, $k_2 = 10$, $k_s = 500$, observer gain $w = 50$.

8.2 Case 1: Step Load Dynamic Response

The DAB was here to be subjected to a severe step load change from 1 kW to 2 kW (with V_{in} held constant rate at 150 V).

- **PI Control:** Exhibited a slow natured settling time of 52 Ms with massive aspects of voltage undershoot of -8.2 V.
- **Classical SMC:** Improved here to be settling time to 22 Ms but demonstrated here as a high steady-state voltage ripple of 2.15 V directly caused by discontinuous natured chattering.
- **ST-SMC:** Achieved in this way an exceptional settling time of just 12 Ms. The voltage undershoot was merely utilised to be restricted to -6.3 V, and the steady-state ripple was drastically suppressed to 0.48 V, proving here as that the super-twisting algorithm successfully smooths the control-based action while retaining speed.

8.3 Case 2: Input Voltage Disturbances

To evaluate line-based regulation, the input voltage was here to be suddenly decreased from 150 V to 120 V under a constant 2 kW load.

- **PI Control:** Required 52 Ms to reject here as the disturbance.

- **Classical SMC:** Rejected the disturbance in this natured in 20 MS but suffered 2.6 V of ripple.
- **ST-SMC:** Settled flawlessly here in 12 MS with a minimal undershoot aspects of -4.1 V and a negligible ripple of 0.21 V, confirming here with supreme robustness to source fluctuations.

8.4 Case 3: Robustness to Severe Parameter Mismatch

Electrolytic output capacitors (C_o) degrade nature here to be more significantly over time. A robustness test was conducted by forcing here as the controller to operate with an internal mathematical model assuming with most inspected thoughts as a capacitance 30% lower than the physical hardware, while trying to executing a 1 kW to 1.5 kW load step.

- **PI Control:** Completely failed here to converge, resulting in persistent oscillations as well as a permanent 4.0 V steady-state error.
- **Classical SMC:** Managed to settle in 13 MS but retained more of a 1.82 V ripple.
- **ST-SMC:** Displayed absolute natured like invariance to the mismatch. It tracked the 450 V reference perfectly here with **zero** steady-state error, settling here in 11 MS with a 0.18 V ripple.

8.5 Case 4: Sensor less Control with Constant Power Loads (CPL)

To validate in this nature of the non-linear disturbance observer, a tightly regulated 1 kW buck converter (acting as a CPL) was more or less violently switched onto a DAB network liked already supplying a 2-kW resistive load.

- **PI-DPC:** The negative aspects here as impedance caused a severe transient crash; the voltage dropped here by -4.0 V as well as took a staggering 230 MS to stabilize.
- **Observer-ST-SMC (SMC+O):** The observer natured here with instantly estimated the current surge. The controller stabilized the DC-link voltage in a mere 110 MS, limiting the transient natured voltage sag to -2.5 V. This confirmed that the sensor less observer-based ST-SMC successfully here to be more of injects virtual positive damping to neutralize CPL instability.

Table 3: Comprehensive Experimental Performance Summary

Test Condition	Control Strategy	Settling Time (MS)	Undershoot/Overshoot (V)	Steady-State Error
Load Step 1-2kW	PI	52	-8.2	0
	Classical SMC	22	-7.6	0
	ST-SMC	**12**	**-6.3**	**0**
Input Drop 150-120V	PI	52	-7.4	0
	Classical SMC	20	-5.6	0
	ST-SMC	**12**	**-4.1**	**0**
Capacitance -30%	PI	N/A	7.6	4.0 V
	Classical SMC	13	7.1	0
	ST-SMC	**11**	**6.5**	**0**
CPL Addition 1kW	PI-DPC	230	-4.0	0
	Classical SMC	175	-3.5	0
	ST-SMC+O	**110**	**-2.5**	**0**

9. CONCLUSION

The dynamic control based of Dual Active Bridge (DAB) DC-DC converters here in modern microgrid applications is plagued by nonlinearities, parameter-based drift, as well as the destabilizing nature of Constant Power Loads in here. This research in this way to be conclusively demonstrates more on this to be traditional linear strategies, such as Proportional-Integral (PI) as well as here with basic Direct Power Control (DPC), are mostly inherently inadequate for handling severe uncertainties, as they tend fail to converge under parameter mismatches. While classical Sliding Mode Control (SMC) offers theoretical here as robustness, its practical implementation induces severe here with high-frequency chattering, unacceptable voltage ripple, as well as here to be switching stress.

The implementation nature of the advanced Super-Twisting Sliding Mode Control (ST-SMC) algorithm fundamentally resolves here as these challenges. By processing more of the integral of the discontinuous sliding variable, ST-SMC yields here as a perfectly smooth and continuous phase-shift modulation command. Experimental validation here on a 2-kW hardware prototype confirms that ST-SMC reduces here to be settling times in this way by up to 75% compared to PI controllers, annihilates steady-state voltage based natured ripple, as well as guarantees absolute reference tracking even when physical aspects here to be capacitance parameters degrade by 30%.

Furthermore, the integration of a nonlinear aspects here to be disturbance observer successfully eliminates the need for physical current natured sensors. The observer here as more or more accurately estimates rapid CPL transients, enabling most of the ST-SMC to dynamically inject virtual positive impedance. This combined prospects here of the observer-based ST-SMC framework provides a highly reliable, chattering-free, as well as fault-tolerant control architecture, establishing in this manner it as a superior solution for next-generation electric vehicles, renewable energy storage, and smart grid applications.

Future Scope: Future research on this study should prioritize integrating adaptive tuning algorithms powered by artificial intelligence to dynamically created more of the update ST-SMC gains in real-time. Additionally, expanding on this robust observer-based ST-SMC framework to multiport based DAB converters which will further facilitate complex bidirectional power routing in decentralized energy networks in this way.

REFERENCES

[1] Ahmad, S., Mekhilef, S., Mokhlis, H., Karimi, M., Pourdaryaei, A., Ahmed, T., Jhuma, U., & Afzal, S. (2021). Fuzzy logic-based direct power control method for PV inverter of grid-tied AC microgrid without phase-locked loop. *Electronics*, 10(24), 3095.

[2] Ataullah, H., Iqbal, T., Khalil, I. U., Ali, U., Blažek, V., Prokop, L., & Ullah, N. (2022). Analysis of the dual active bridge-based DC-DC converter topologies, high-frequency transformer, and control techniques. *Energies*, 15(3), 1-25.

[3] Bagheri, F., Güler, N., Komurcugil, H., & Bayhan, S. (2023). An adaptive sliding mode control for a dual active bridge converter with extended phase shift modulation. *IEEE Access*, 2(2), 1–11.

[4] Bandyopadhyay, B., Janardhanan, S., & Spurgeon, S. K. (2013). *Advances in sliding mode control*. Springer.

[5] Batool, M., Hassan, W., & Lu, D. (2024). Review of advanced control strategies for isolated DC-DC converters in DC microgrids. *IEEE Access*, 1–21.

[6] Bayhan, S., &Komurcugil, H. (2019). A sliding-mode controlled single-phase grid-connected quasi-Z-source NPC inverter with double-line frequency ripple suppression. *IEEE Access*, 7, 1-10.

[7] Bouafia, A., & Krim, F. (2008). A fuzzy-logic-based controller for three-phase PWM rectifier with unity power factor operation. *Journal of Electrical Systems*, 4(1).

[8] Bouafia, A., Krim, F., & Gaubert, J.-P. (2009). Fuzzy-logic-based switching state selection for direct power control of three-phase PWM rectifier. *IEEE Transactions on Industrial Electronics*, 56(6), 1984–1992.

[9] Chan, J. (2022). Sliding mode control of brushless DC motor speed control. *Malaysian Journal of Science and Advanced Technology*, 2(4), 188–193.

[10] Chen, W.-H., Yang, J., Guo, L., & Li, S. (2016). Disturbance-observer-based control and related methods-An overview. *IEEE Transactions on Industrial Electronics*, 63(2), 1083-1095.

[11] Choi, D.-K., & Lee, K.-B. (2015). Dynamic performance improvement of AC/DC converter using model predictive direct power control with finite control set. *IEEE Transactions on Industrial Electronics*, 62(1), 757–767.

[12] Das, S., Qureshi, M. S., & Swarnkar, P. (2018). Design of integral sliding mode control for DC-DC converters. *Materials Today: Proceedings*, 5(2), 4290–4298.

[13] de Brito, M., Dourado, E., Sampaio, L., Oliveira da Silva, S., & Cordero, R. (2023). Sliding mode control for single-phase grid-connected voltage source inverter with L and LCL filters. *Eng*, 4(1), 301–316.

[14] Esteban, F., Serra, F., & De Angelo, C. (2021). Control of a DC-DC dual active bridge converter in DC microgrids applications. *IEEE Latin America Transactions*, 19(3), 1261–1269.

[15] Gong, S., Li, X., Han, J., Sun, Y., Xu, G., Jiang, Y., & Huang, S. (2021). Sliding mode control based decoupling scheme for quad-active bridge DC-DC converter. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 2(1), 1–12.

[16] Gu, J., & Pan, S. (2024). Sliding mode control of dual active bridge converter based on hyperbolic tangent function. *Journal of Physics: Conference Series*, 2803(2), 012050.

[17] Hamza, A., & Krim, F. (2012). Comparison between PI and fuzzy DPC control of a shunt active power filter. In *2012 IEEE International Energy Conference and Exhibition (ENERGYCON)*, 146–151.

[18] Jatoth, R., & Mangu, B. (2024). Performance enhancement of dual active full-bridge converter with advanced control modules for V2G and G2V application. *International Journal of Engineering Trends and Technology*, 72(2), 232–242.

[19] Kazemi, M., Moradi, M., & Kazemi, R. (2014). Fuzzy logic control to improve the performance of the direct power control based DFIG. *COMPEL: The International Journal for Computation and Mathematics in Electrical and Electronic Engineering*, 33(1–2).

[20] Luo, B.-Y., Subroto, R., Wang, C.-Z., & Lian, K.-L. (2022). An improved sliding mode control with integral surface for a modular multilevel power converter. *Energies*, 15(5), 1704.

[21] Mohammed, K., Semmah, A., Wira, P., & Dahmani, S. (2020). Fuzzy logic-based instantaneous power ripple minimization for direct power control applied in a shunt active power filter. *Electrical Engineering*, 102(1), 1-12.

[22] Mujammal, M., Abdelhafidh, M., Wira, P., Albasheri, M., & Cherifi, A. (2024). Novel direct power control based on grid voltage modulated strategy using artificial intelligence. *Smart Grids and Sustainable Energy*, 9(2), 1-15.

[23] Sami, I., Alhosaini, W., Khan, D., & Ahmed, E. (2024). Advancing dual-active-bridge DC–DC converters with a new control strategy based on a double integral super twisting sliding mode control. *World Electric Vehicle Journal*, 15(8), 348.

[24] Sayeh, K. F., Tamalouzt, S., Ziane, D., Deffaf, B., Lalouni, S., Belkhier, Y., Bajaj, M., & Blažek, V. (2024). Fuzzy logic-enhanced direct power control for wind turbines with doubly fed induction generators. *Results in Engineering*, 2(4).

[25] Shao, S., Chen, L., Shan, Z., Gao, F., Chen, H., Sha, D., & Dragicevic, T. (2021). Modeling and advanced control of dual active bridge DC-DC converters: A review. *IEEE Transactions on Power Electronics*, 8(2), 1–18.

[26] Yan, S., Yang, Q., Zhang, H., & Li, C. (2023). Improved single-loop SMC strategy with hybrid sliding surface and torque observer for double-controlled DFIG. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 2(2), 1-12.

[27] Yang, M., & Liu, P. (2023). Research on sliding mode control of dual active bridge converter based on linear extended state observer in distributed electric propulsion system. *Electronics*, 12(2), 3522.